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FINAL REPORT

Passive Microwave Spectral Imaging of Atmospheric Structure

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Passive Microwave Spectral Imaging of Atmospheric Structure

ABSTRACT

The primary objective of this research was to improve the scientific foundation necessary to full realization of the meteorological potential of the NOAA Advanced Microwave Sounding Unit (AMSU) recently first launched on the NOAA-15 satellite in May, 1998. These advances were made in four main areas: 1) improvements, based on aircraft observations, in the atmospheric transmittance expressions used for interpreting AMSU and similar data, 2) development of neural network retrieval methods for cloud top altitude estimates of ~1-km accuracy under cirrus shields--the altitude is that of the larger ice particles aloft, which is related to precipitation rate, 3) analysis of early AMSU flight data with respect to its precipitation sensitivity and fine-scale thermal structure, and 4) improvements to the 54-GHz and 118-GHz MTS aircraft imaging spectrometer now operating on the NASA ER-2 aircraft.

More specifically, the oxygen transmittance expressions near 118 GHz were in better agreement with aircraft data when the temperature dependence exponent of the 118.75-GHz linewidth was increased from the MPM92 value (Liebe et al., 1992) of 0.8 to 0.97±0.03. In contrast, the observations 52.5-55.8 GHz were consistent with the MPM92 model. Neural networks trained on comparisons of 118-GHz spectral data and coincident stereoscopic video images of convective cells observed from 20-km altitude yielded agreement in their peak altitudes within as little as 1.36 km rms, much of which is stereoscopic error. Imagery using these methods produced useful characterizations for Cyclone Oliver in 1993 and other storms (Schwartz et al., 1996; Spina et al., 1998). Similar neural network techniques yielded simulated rms errors in relative humidity retrievals of 6-14 percent over ocean and 6-15 percent over land at pressure levels from 1013 to 131 mbar (Cabrera-Mercader and Staelin, 1995).

Early AMSU data have revealed a marked ability to sense precipitation, a capability now being studied further under separate sponsorship. It also clearly revealed nearly fully resolved warmings over most hurricanes examined to date, where these warmings are linked to storm dynamics and wind energy. Improvements to MTS supported NAST-M, which was completed and then successfully operated over hurricanes and other storms during CAMEX-3, August-September 1998, in combination with a new high-performance infrared interferometer, NAST-I.

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I. INTRODUCTION

This research program extended work done under NASA Grant NAG 5-10 by capitalizing on improvements in aircraft and space sensors and in remote sensing retrieval techniques. New aircraft-based microwave atmospheric transmittance measurements were made looking toward zenith rather than downward, thus significantly increasing their accuracy. A strong foundation for future studies was also established based on Advanced Microwave Sounding Unit (AMSU) satellite data from the operational NOAA-15 satellite and on the improved Microwave Temperature Sounder (MTS) portion of the NPOESS Airborne Sounder Testbed (NAST), both of which began operation in the final days of this program. Results from each of the four major thrusts of this effort are described below: 1) oxygen transmittance measurements near 54 and 118 GHz, 2) cloud-top altitude estimation using aircraft 118-GHz spectra, 3) preliminary analysis of NOAA-15 AMSU data (23-190 GHz), and 4) improvements to MTS at 54 and 118 GHz.

II. OXYGEN TRANSMITTANCE STUDIES

Prior investigators have noticed in aircraft and spacecraft microwave data systematic discrepancies between measured and simulated upwelling brightness temperatures as large as several degrees Kelvin near the 54- and 118-GHz oxygen absorption bands; the simulations are based upon simultaneous co-located radiosonde observations. The increasing importance of microwave observations to synoptic and climatic studies has made such discrepancies unacceptable. The transmittance studies reported here suggest that these discrepancies are not due principally to transmittance errors, but rather to unknown instrument calibration errors or similar causes. A small adjustment to current transmittance expressions is also suggested. The following work was documented extensively (M. J. Schwartz, PhD thesis, MIT Dept. of Physics, 1997).

All transmittance observations were made from the NASA ER-2 aircraft flying to and from 65,000 feet altitude. The zenith-viewing experiment configuration employed here is several times more sensitive to atmospheric transmittances than the nadir-viewing configuration employed previously. This follows because the difference between nominal atmospheric temperatures of 220-270K and the 2.7K background at zenith is 4-20 times greater than the difference between atmospheric temperatures and the 280K background at nadir; this contrast is roughly proportional to transmittance sensitivity.

The Microwave Temperature Sounder (MTS) used for these observations included two superheterodyne receivers: one with eight IF channels covering 350-2000 MHz from the center of the 118.75-GHz oxygen line, and the other with a single-channel 30-200 MHz IF and a tunable local oscillator stepped non-uniformly through eight frequencies (channels) centered from 52.7 to 55.6 GHz.

The 118-GHz system employed a scalar feed antenna and a small fixed parabolic mirror at 45 degrees with a 7.5-degree beamwidth. This beam was then scanned ±46.8 degrees cross-track from zenith by means of a rotating flat mirror angled at 45 degrees to the beam. This beam was scanned 360 degrees every 5.5 seconds at variable speed, viewing both a hot and an ambient temperature load each cycle. The 118-GHz signal was also chopped at 25 Hz against a Dicke reference load by a rotating half-mirror located between the feed and the scanning mirror. A frequency-tripled Gunn local oscillator drove a balanced Schottky diode mixer at 118.75 GHz. Approximately 70 dB of gain was provided by the IF amplifiers, followed by an eight-way power divider and filters for each channel. Detectors, video amplifiers, Dicke commutators, and sample/hold circuits for each channel then fed the multiplexer, A/D converter, and computer. This instrument was upgraded but retained substantially the same architecture it had when flown on the GALE and early COHMEX deployments, as documented previously (A.J. Gasiewski et al., Journ. Applied Meteorology, 29(7), 1990; A. J. Gasiewski, PhD thesis, MIT, Dept. of EECS, 1988). One complication was that a defective contact at the output of the IF amplifier reduced the gain at lower IF frequencies and introduced additional ripple into the channel passbands. This ripple had to be calibrated post-flight, and the data interpreted accordingly, allowing for the strong frequency dependence of atmospheric transmittances across individual channels. Frequency drift of the local oscillator with time and temperature also required measurement and consideration.

The "53-GHz" instrument had a tunable local oscillator which permitted its 30-200 MHz IF double sidebands to be moved through much of the range from 52.5 to 55.7 GHz under computer control. The 10.3-degree (FWHM) antenna beam viewed only zenith with a 93-percent beam efficiency (within 2.5 times the 3-dB point) and a 5-percent return loss; the antenna was a scalar feed capped by a rexolite lens designed for use on the NIMBUS-5 satellite at 53.65 GHz. 97.2 percent of the power was received within 58.5 degrees of zenith. The antenna was followed by three ferrite circulator switches in series which provided isolation plus three ports viewing the antenna, a hot load, and an ambient temperature load. The varactor-tuned Gunn oscillator operated 52.8-55.5 GHz and permitted approximate simulation of channels 3-7 of the Advanced Microwave Sounding Unit A (AMSU-A). The IF amplifier was followed by a detector, video amplifier, Dicke commutator, gated integrator, and the same A/D converter and computer used at 118 GHz.

The data used for analysis came principally from three days in September, 1993, two flights being over Virginia and one over California. Each flight provided ascent and descent data, and was coincident with one or more radiosondes.

The data near 54 GHz was consistent with predictions based upon local radiosondes and the MPM92 atmospheric absorption model of Liebe et al. (H. H. Liebe, P. W. Rosenkranz, and G. A. Hufford, J. Quant. Spectroscopy and Radiative Transfer, 48, Nov.-Dec., p. 629, 1992). Similar comparisons near 118 GHz are most consistent with adjustment of the temperature-dependent exponent of the 118.75-GHz linewidth from the MPM92 model value of 0.8 to the new value of 0.97±0.03. This increase in low-temperature linewidth changes total atmospheric opacity in these channels by less than 2.5 percent. This increased opacity is substantially less than previous suggestions that corrections of up to 20 percent might be required. These new values are sufficiently accurate to warrant processing AMSU data with some confidence. Additional improvements in transmittance accuracy are expected from measurements to be obtained with the improved NAST-MTS discussed here in Section V.

III. 118-GHZ CLOUD-TOP ALTITUDE ESTIMATION

It is well known that cloud-top altitudes of unobscured convective cells are strongly correlated with precipitation rate (e.g. G. A. Vicente, R. A. Scofield, and W. P. Menzel, Bull. Amer. Meteor. Soc., 79, p1883, Sept., 1998), and so new satellite-based methods that probe such cell-top altitudes through overlying cloud shields can potentially measure precipitation more accurately.

Near 118 GHz graupel scatters strongly and can exhibit brightness temperatures below 100K because it reflects well the extremely low brightness temperature of space, 2.7K. These low temperature signatures are observable from aircraft or spacecraft flying overhead only if the cloud tops penetrate to sufficiently high altitudes. Channels close to the opaque 118-GHz oxygen resonance respond only to the very highest altitude clouds, while those channels in the wings up to 2 GHz from line center penetrate the atmosphere more deeply and respond to nearly all clouds. Thus by comparing the visibility of convective cells at several frequencies (opacities) it is possible to estimate the cell-top altitude. The area covered by the cell top is also of interest, for it is roughly proportional to the total cell rain rate. It is expected that fusion of cell altitude and area observations should permit usefully accurate measurements of integrated cell rain rates (m^3/sec). Similar interpretation of

AMSU 183-GHz water vapor data from the NOAA-15 satellite following the conclusion of this program has yielded very promising comparisons on a cell basis with NEXRAD observations, with rainfall-weighted rms discrepancies in total cell rain rates below 3 dB.

The 118-GHz cell-top altitude observations were made using MTS on the NASA ER-2 aircraft, flying near 20-km altitude, during the Genesis-of-Atlantic-Lows Experiment (GALE) and the Cooperative Huntsville Meteorological Experiment (COHMEX), 1986. Eight 200-MHz wide channels were employed with IF frequency bands centered at 0.50, 0.66, 0.84, 1.04, 1.26, 1.47, 1.67, and 1.9 GHz from the line center at 118.75 GHz. Cloud signatures were manifest as cold spots relative to a constant temperature background, which varied slightly with frequency and scan angle. These cold perturbations for each spot and channel were fed to a neural network that estimated cell top height.

The neural network employed 4 hidden nodes in one layer when only spatial brightness perturbations were used as input, and 5 hidden nodes when the 8 absolute brightness temperatures were also input. Observations of the centers of 117 summer and winter clouds were used to train the network, and a completely different 59 were used to evaluate it; these numbers were reduced to 56 and 28, respectively, when only cumulus clouds were evaluated. Improved altitude-estimation performance was obtained when only cumulus clouds were considered, and slightly more when observed brightness temperatures supplemented the cold perturbations as input; still further improvement resulted when the input included the diameter (km) of the cold perturbation.

For these four cases the rms errors for the test sets of clouds were 1.76, 1.44, 1.41, and 1.36 km, respectively, when compared to the cloud top altitudes estimated using a nadir-viewing video camera and parallax computations. These visible cloud top altitudes are estimated to be accurate to perhaps 1 km due to errors in signal processing, the estimated relative velocity between cloud and aircraft, and the estimated aircraft altitude, suggesting the 118-GHz determinations might be as accurate as 1 km rms. Special techniques were developed to train these neural networks with limited data in a robust manner.

These observations and techniques were described by Spina (M. S. Spina, SM thesis, MIT Dept. of EECS, Sept., 1994) and by Spina et al., (M. S. Spina, M. J. Schwartz, D. H. Staelin, and A. J. Gasiewski, IEEE Trans. on Geoscience and Remote Sensing, 36, p154, Jan, 1998). The same publications also presented cloud-top altitude maps viewed by MTS over cyclone Oliver (February 7, 1993) northeast of Australia. An example is presented here in Figure 1. These tops of the graupel distribution are clearly morphologically different from those viewed by GOES or similar IR sensors which respond strongly to much smaller ice particles.

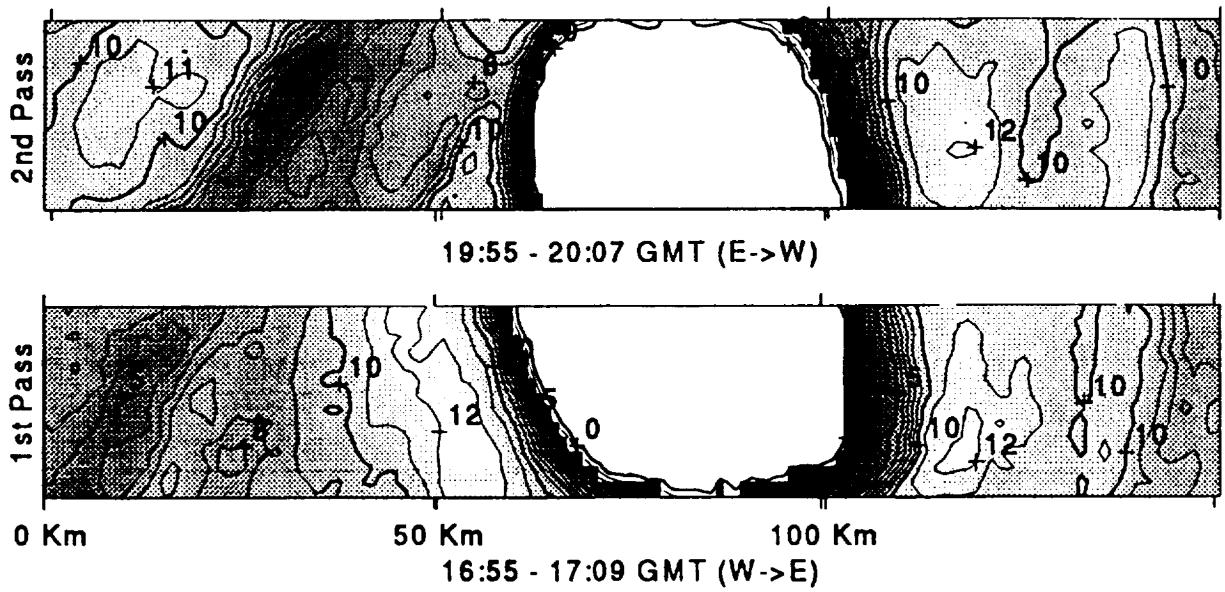

Figure 1. Retrieved cloud-top altitudes for cyclone Oliver

These techniques appear to be very promising for characterizing convective precipitation using future polar and geostationary passive microwave satellite instruments such as the proposed Advanced Technology Microwave Sounder (ATMS) being developed for NASA and NPOESS, and the proposed GEostationary Microwave sounder (GEM), both of which are proposed to carry temperature sounding channels with ~30-km spatial resolution or better (20 km nominal).

IV. PRELIMINARY ANALYSIS OF AMSU DATA FROM NOAA-15

NOAA-15 was launched in May, 1998 and began producing AMSU data almost immediately. Initial examination revealed small software and interference problems which were largely corrected or compensated to yield preliminary scientific results. The two most important conclusions from this brief study are that the 15-km spatial resolution and sampling interval of AMSU B is sufficient to usefully characterize most rain cells and other fine-scale microwave meteorological phenomena, and that the 183-GHz channels are excellent probes of precipitation when they have adequate spatial resolution and sampling density. Subsequent preliminary studies have revealed surprisingly good agreement (better than 3 dB) between AMSU-B and NEXRAD-based estimates of total cell-centered regional rain rate (cubic meters per second).

Figure 2 presents bilinearly interpolated AMSU-B images of Typhoon Rex at 183±7 and 183±1 GHz. The blue regions generally correspond to rain and originate from either absorption by cold rain aloft or from cell-top graupel that reflects cold space. The rain signature at the more opaque 183±1 GHz channel corresponds to ice scattering at temperatures sufficiently low that only significant updrafts could inject graupel so high, implying local regions of higher rain rate. The calibration employed is preliminary and does not correct for interference from the data transmitters on NOAA-15.

V. IMPROVED MIT MICROWAVE TEMPERATURE SOUNDER, MTS

The NASA/NOAA/DoD Integrated Program Office (IPO) has undertaken development of the nation's next generation polar orbiting meteorological system (NPOESS), and in support of that has funded construction of an improved version of the MTS described above. This effort also supported that development, with emphasis on design and testing. In particular, the many lessons learned during the careful calibration and data analysis for the oxygen transmittance experiments described above were applied. Improvements were made in calibration accuracy, linearity, sensitivity, and interference rejection. The new three-point calibration scheme (hot and cold loads, plus cold space) has been particularly helpful. The difficult-to-use custom software previously employed for MTS data manipulation and analysis was largely replaced by efficient MatLab scripts. The improved MTS has subsequently successfully flown more than ten missions, several over hurricanes, and is yielding excellent imagery near both 54 and 118 GHz; each band has 8 channels and is well calibrated.

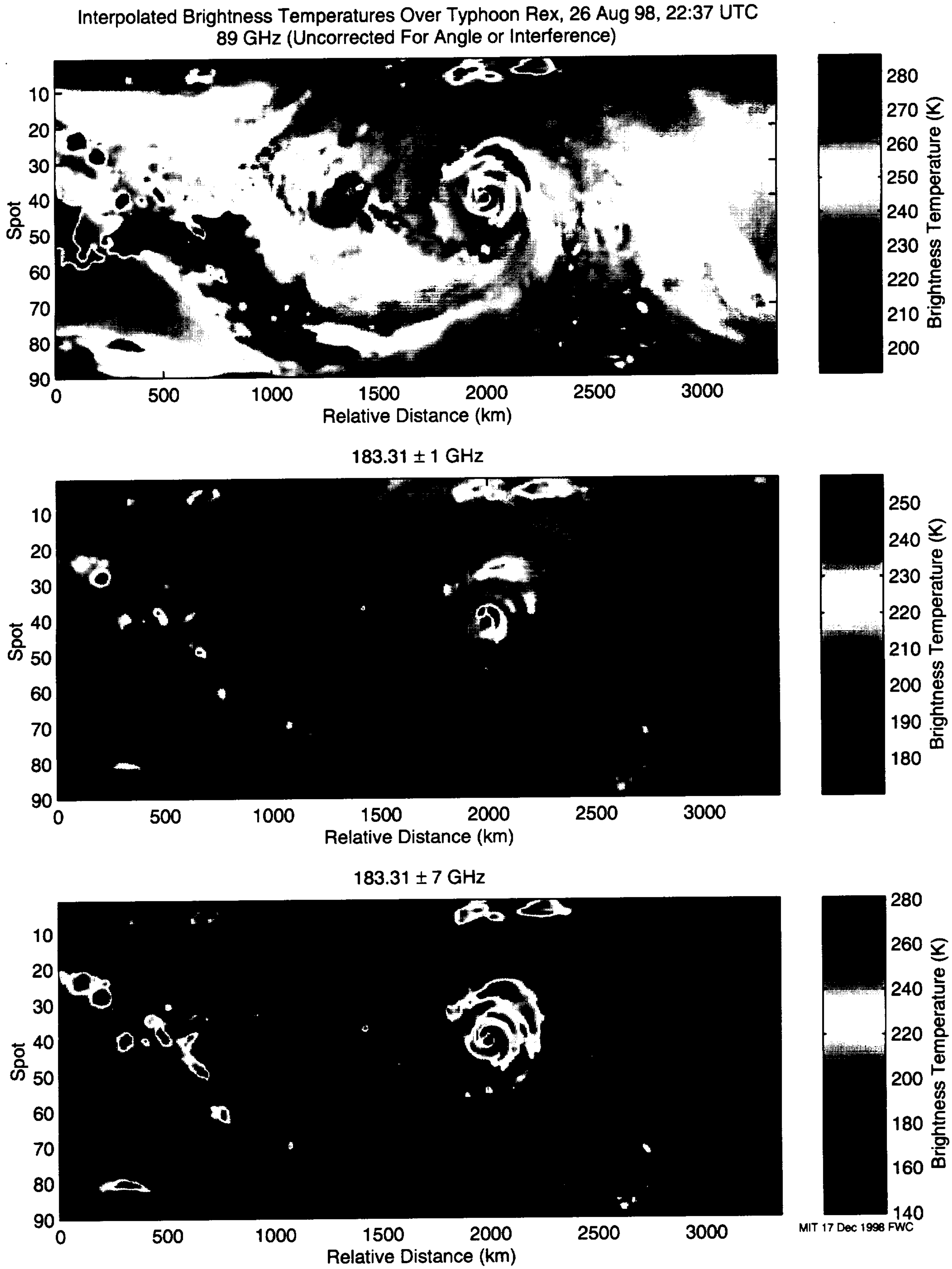

Figure 2: Typhoon Rex viewed by AMSU near 89, 183±1, 183±7 GHz.

Appendix A

Observations of Thermal and Precipitation Structure in a Tropical Cyclone by Means of Passive Microwave Imagery near 118 GHz

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Abstract

An imaging microwave radiometer with eight double-sideband channels centered on the 118-GHz oxygen resonance was flown on a high-altitude aircraft over a tropical cyclone in the Coral Sea. The measurements clearly resolved an eyewall of strong convection and a warm core within the eye. Brightness temperatures observed within the eye were approximately 10 K warmer than those observed in clear air 100 km or more away. This warming extended somewhat beyond the eyewall in the highest (most opaque) channel. The temperature profile in the eye, central pressure, and convective cell-top altitudes are inferred from the data.

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Appendix B

Application of Multilayer Feedforward Neural Networks to Precipitation Cell-Top Altitude Estimation

Michelle S. Spina, Michael J. Schwartz, David H. Staelin, and Albin J. Gasiewski

Abstract

The use of passive 118-GHz O2 spectral observations of rain cells for precipitation cell-top altitude estimation is demonstrated by using a multilayer feedforward neural network retrieval system. Rain cell observations at 118 GHz were compared with estimates of the cell-top altitude obtained by optical stereoscopy. The observations were made with 2-4-km horizontal spatial resolution by using the millimeter-wave temperature sounder (MTS) scanning spectrometer aboard the NASA ER-2 research aircraft, during the Genesis of Atlantic Lows Experiment (GALE) and the Cooperative Huntsville Meteorological Experiment (COHMEX) in 1986. The neural network estimator applied to MTS spectral differences between clouds, and nearby clear air yielded an rms discrepancy of 1.76 km for a combined cumulus, mature, and dissipating cell set and 1.44 km for the cumulus-only set. An improvement in rms discrepancy to 1.36 km was achieved by including additional MTS information on the absolute atmospheric temperature profile. An incremental method for training neural networks was developed that yielded robust results, despite the use of as few as 56 training spectra. Comparison of these results with a nonlinear statistical estimator shows that superior results can be obtained with a neural network retrieval system. Imagery of estimated cell-top altitudes was created from 118-GHz spectral imagery gathered from CAMEX, September through October, 1993, and from cyclone Oliver, February 7, 1993.

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Appendix C

Observation and Modeling of Atmospheric Oxygen Millimeter-wave Transmittance

Michael Jonathan Schwartz

Submitted to the Department of Physics
on September 15, 1997, in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy in Physics

Abstract

The Microwave Temperature Sounder (MTS) was used on multiple ascents and descents of NASA ER-2 aircraft to measure downwelling thermal atmospheric emission viewed from 0-20-km altitudes in millimeter-wave bands dominated by molecular oxygen, and to infer atmospheric opacity in these bands. The MTS includes two super-heterodyne receivers: one with eight IF channels covering 350-2000 MHz from the 118.75-GHz oxygen line and the other with a 30-200-MHz IF and a tunable LO stepped through eight frequencies from 52.7-55.6 GHz. Simulations of MTS zenith-view antenna temperatures based upon local radiosondes and the MPM92 absorption model of Liebe, et al. [50] were consistent with observations in the 52.5-55.8 GHz band. Adjustment of the temperature dependence exponent of the 118.75-GHz linewidth from the MM92 value of 0.8 to 0.97 ± 0.03 was found to produce significantly better agreement in observations with MTS channels centered on this line. This increase in low-temperature linewidth changes total atmospheric opacity in these channels by less than 2.5 percent.

Other investigators have noted systematic discrepancies as large as several Kelvin between measured and simulated **upwelling** brightness temperatures, both in satellite observations of the earth in the 50-60 GHz band and in nadirial-viewed MTS observations from 20-km altitude in the band 116.7-120.8 GHz. Resolution of these biases through adjustment of the oxygen absorption model requires increases in the MPM92 expression of up to 20 percent. The utility of current and proposed satellite-based millimeter-wave temperature sounders for the monitoring of global climate, the initialization of numerical weather models, and the remote monitoring of severe weather systems is compromised by this model uncertainty.

The zenith-viewing configuration through ascents and descents of the current MTS measurements are several times more sensitive to perturbation of atmospheric opacity than are space-based observations. The implication of the current results is that errors in the oxygen absorption model are not the source of observed discrepancies Reexamination of the satellite instruments' response characteristics is indicated.

Thesis supervisors: David H. Staelin, Professor of Electrical Engineering, and
Bernard F. Burke, Professor of Physics

Appendix D

Application of Multilayer Feedforward Neural Networks to Precipitation Cell-Top Altitude Estimation

Michelle S. Spina

Submitted to the
Department of Electrical Engineering and Computer Science
on September 1, 1994, in partial fulfillment of the
requirements for the degree of
Master of Science in Electrical Engineering

Abstract

The use of passive 188-GHz O2 spectral observations of rain cells for precipitation cell-top altitude estimation is demonstrated using a multilayer feedforward neural network retrieval system. Data was derived from a collection of 118-GHz rain cell observations along with estimates of the cell-top altitude obtained by optical stereoscopy. The observations were made using the millimeter-wave temperature sounder (MTS) scanning spectrometer aboard the NASA ER-2 research aircraft, flying near 20 km altitude, during the Genesis-of-Atlantic-Lows-Experiment (GALE) and the Cooperative-Huntsville-Meteorological-Experiment (COHMEX), 1986. The neural network estimator applied to MTS spectral differences between clouds and nearby clear air yielded an RMS discrepancy of 1.76 km for a combined cumulus, mature and dissipating cell set and 1.44 km for the cumulus-only set. An additional improvement in RMS discrepancy to 1.36 km was achieved by including additional MTS information on the absolute atmospheric temperature profile. An incremental method for training neural networks was developed which yielded robust results despite the use of as few as 56 training spectra. Comparison of these results with a nonlinear statistical estimator shows that superior results can be obtained with a neural network retrieval system. The neural network estimator was then used to create imagery of cell-top altitudes estimated from 118-GHz CAMEX spectral imagery gathered from September through October, 1993, and from spectral imagery gathered from cyclone Oliver on February 7, 1993.

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